MOVING MAGNET TYPE PLANAR MOTOR CONTROL

FIELD OF THE INVENTION

The invention relates to planar motors. More particularly, the invention is related to a control system for a moving magnet type planar motor.

BACKGROUND OF THE INVENTION

Precision systems, such as those used in semiconductor processing, inspection and testing, often use linear motors for positioning objects such as semiconductor wafers. Conventional precision systems include separate, stacked stages that permit movement along perpendicular axes (*i.e.*, an "X" stage stacked on a "Y" stage). These systems typically are complex, heavy and inefficient in operation. Improved object positioning, particularly for use in lithographic instruments, has been realized through the use of planar motors, which advantageously permit simplicity in design, weight savings, as well as enhanced precision and efficiency. Such a linear or planar motor, in principle, operates in accordance with the Lorentz law, which relates the force on a charged particle to its motion in an electromagnetic field. An object such as a stage in a lithography system may be translated or propelled using the electromagnetic force generated by a wire or coil carrying an electric current in a magnetic field. The planar motor provides a single stage to replace conventional stacked stages, with the stage being electromagnetically suspended or levitated for enhanced performance and versatility.

Planar motors typically include a magnet array and a coil array. Several basic designs for planar motors are known, and are distinguished based on which of the components are positionally fixed and which move with respect thereto. In a first design, commonly referred to as a "moving coil type" planar motor, the coil array moves with respect to a positionally fixed magnet array. In one embodiment, as disclosed in U.S. Patent No. 6,097,114 to Hazelton and shown schematically in **Fig. 1**, a moving coil planar motor **100** includes a base **102** with a flat magnet array **103** having a plurality of magnets **104**. A single X coil **106** and two Y Coils **108, 110** are attached to the underside of a stage frame **112** (drawn in dashed lines) suspended above and parallel to magnet array **102**. Y coils **108, 110** are similar in structure to one another and have coil wires oriented to provide force substantially in a Y direction. X coil **106** and Y coils **108, 110** are similar in structure, but X coil **106** has coil wires oriented to provide force substantially in an X direction perpendicular to the Y direction.

X coil **106** and Y coils **108, 110** permit movement of stage frame **112**. To provide force to stage frame **112** in the X direction relative to magnet array **102**, two phase, three phase, or multiphase commutated electric current is supplied to X coil **106** in a conventional manner by a commutation circuit and current source **114**. To provide force to stage frame **112** in the Y direction, two phase, three phase, or multiphase commutated electric current is supplied to either one or both of the Y coils **108, 110** in a conventional manner by respective commutation circuits and current sources **116** and/or **118**. To provide rotational torque to frame **112** relative to magnet array **102** in a horizontal plane parallel to the X and Y axes, commutated electric current is supplied to either of Y coils **108, 110** individually by respective commutation circuits and current source **116** or **118**. Alternatively, electric current is supplied to both Y coils **108, 110** simultaneously but with opposite polarities by respective commutation circuits and current sources **116, 118**, providing Y force to one of Y coils **108, 110** in one direction and the other Y coil **108, 110** in an opposite direction, thereby generating a torque about an axis normal to the XY plane. This torque typically causes rotation of stage frame **112** in the XY plane.

In a second design, also disclosed in U.S. Patent No. 6,097,114 to Hazelton and shown schematically in **Fig. 2**, a "moving magnet type" planar motor includes a magnet array that moves with respect to a positionally fixed coil array. In one embodiment, moving magnet planar motor **200** includes an upper surface of a flat base **202** that is covered with coil units **204**. A positioning stage **206** is suspended above flat base **202** and has an array of magnets **208** facing the upper surface of flat base **202**. A conventional commutation circuit (not shown) controls and supplies electric current to coil units **204** in accordance with the desired direction of travel of positioning stage **206**. Appropriately commutated electric current creates Lorentz forces, which propel positioning stage **206** to a desired location, altitude, and attitude.

Suspension of a stage **112, 206** may be accomplished using a variety of techniques. For example, additional, permanent magnets may be provided on the upper surface of a stage **112, 206** and on a stationary frame located above the stage **112, 206** (not shown). Alternatively, an air bearing may be provided between a stage **112, 206** and its respective base **102, 202**. Electromagnetic force generated by the motor may instead provide the necessary suspension force.

Despite these developments, there is a need for a planar motor control that simultaneously controls translational forces in the X- and Y- directions and θ_z rotational movement. In addition, in order to achieve smooth operation of planar motors, rigorous computational power must be provided. For example, complex mathematical relationships

must be evaluated to achieve the desired torque and translation in the X and Y directions. To this end, significant CPU power typically is required. A need exists, therefore, for planar motor control using relationships with less complexity.

Also, there is a need for a planar motor control that permits torque control with very low force ripple.

SUMMARY OF THE INVENTION

The present invention is related to a planar motor including a coil array having a plurality of coils, each coil fixed in position with respect to the other coils, and a magnet array having a plurality of magnets, each magnet fixed in position with respect to the other magnets, with the magnet array being movable above the coil array in at least two degrees of translational freedom and at least one degree of rotational freedom. The planar motor further includes a model-based predictive torque controller including a nonlinear current switching model, with the torque controller configured to provide current to energize each coil in response to the position of each magnet with respect to a coil. The torque controller provides currents to the coil array to at least substantially reduce force ripple during movement of the magnet array.

The torque controller may simultaneously stabilize translational and rotational movement, and may compensate for torque produced by translation. The coil array may be square., and may include at least 25 coils.

The present invention also is related to a method for controlling a planar motor for movement in three degrees of freedom. The method includes: positioning a movable magnet array over a fixed coil array, the coil array having coils generally disposed in a plane defining first and second directions that are substantially orthogonal to one another, and the magnet array having magnets with magnetic fields; applying currents to the coils following a nonlinear current switching model to control movement of the magnet array and substantially reduce force ripple during the movement. The method may further include determining a first translational force for the magnet array in the first direction and a second translational force for the magnet array in the second direction. In addition, the method may include determining a torque for the magnet array in a third direction perpendicular to the first and second directions.

The present invention further is related to a planar motor including magnet array means, coil array means, and control means providing electric current to the coil array means for controlled movement of the magnet array means in three degrees of freedom

including non-linear current switching means for at least substantially reducing force ripple during movement of the magnet array.

The present invention also is related to a stage system including a planar motor. The planar motor includes: a coil array having a plurality of coils, each coil fixed in position with respect to the other coils; a magnet array having a plurality of magnets, each magnet fixed in position with respect to the other magnets, the magnet array being movable above the coil array in at least two degrees of translational freedom and at least one degree of rotational freedom; and a model-based predictive torque controller comprising a nonlinear current switching model, the torque controller configured to provide current to energize each coil in response to the position of each magnet with respect to a coil. The torque controller provides currents to the coil array to at least substantially reduce force ripple during movement of the magnet array.

Furthermore, the present invention is related to an exposure apparatus including an illumination system that supplies radiant energy and a stage system including a planar motor. The planar motor includes: a coil array having a plurality of coils, each coil fixed in position with respect to the other coils; a magnet array having a plurality of magnets, each magnet fixed in position with respect to the other magnets, the magnet array being movable above the coil array in at least two degrees of translational freedom and at least one degree of rotational freedom; and a model-based predictive torque controller comprising a nonlinear current switching model, the torque controller configured to provide current to energize each coil in response to the position of each magnet with respect to a coil. The torque controller provides currents to the coil array to at least substantially reduce force ripple during movement of the magnet array, and the stage system carries at least one object disposed on a path of the radiant energy. A device can be manufactured with the exposure apparatus. Any of a variety of devices such as semiconductor chips (*e.g.*, integrated circuits or large-scale integrations), liquid crystal panels, CCDs, thin film magnetic heads, or micro-machines, can be manufactured with the exposure apparatus.

The present invention additionally is related to a wafer including an image, wherein the image is formed with an exposure apparatus that includes an illumination system that supplies radiant energy and a stage system that includes a planar motor. The planar motor includes: a coil array having a plurality of coils, each coil fixed in position with respect to the other coils; a magnet array having a plurality of magnets, each magnet fixed in position with respect to the other magnets, the magnet array being movable above the coil array in at least two degrees of translational freedom and at least one degree of rotational freedom; and a model-based predictive torque controller comprising a nonlinear

current switching model, the torque controller configured to provide current to energize each coil in response to the position of each magnet with respect to a coil. The torque controller provides currents to the coil array to at least substantially reduce force ripple during movement of the magnet array, and the stage system carries at least one object disposed on a path of the radiant energy.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred features of the present invention are disclosed in the accompanying drawings, wherein similar reference characters denote similar elements throughout the several views, and wherein:

Fig. 1 is a perspective view schematically showing a prior art moving coil planar motor;

Fig. 2 is a perspective view schematically showing a prior art moving magnet planar motor;

Fig. 3 is a perspective view showing a moving magnet planar motor according to an embodiment of the present invention disposed at an initial position with respect to the coil array;

Fig. 4 is a plan view of the magnet array of Fig. 3;

Fig. 5 is a plan view of the magnet array of Fig. 3 disposed above a coil array, forming a planar motor;

Fig. 6 is a graph showing the magnet force constant of the planar motor of Fig. 5;

Fig. 6A is a graphical representation of a moving magnet force constant coefficient;

Fig. 6B is a graphical representation of the Im x component of the magnetic force constant;

Fig. 6C is a graphical representation of the Im y component of the magnetic force constant;

Fig. 7 is a partial plan view of the planar motor of Fig. 5 with one row of magnets and one row of coils;

Fig. 8 is a plan view of the magnet array of Fig. 3 disposed at another position with respect to the coil array;

Fig. 9 is an exemplar graph showing undesired torque behavior;

Fig. 9A is an exemplar graph related to torque compensation;

Fig. 9B is another exemplar graph related to torque compensation;

Fig. 10 is an exemplar graph showing torque compensation according to the present invention;

Fig. 11 is an exemplar graph showing translation compensation according to the present invention;

Fig. 12 is a block diagram of a position control system using an exemplary array of thirty-six coils in accordance with the present invention;

Fig. 13 is an elevational view, partially in section, showing a microlithographic apparatus in accordance with the present invention;

Fig. 14 is a flowchart showing the fabrication of semiconductor devices; and

Fig. 15 is a flowchart showing details of the wafer processing step of Fig. 14.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring initially to **Fig. 3**, there is shown a perspective view of a moving magnet embodiment of a planar motor **300** including such a square flat planar coil array **302**. Moving magnet planar motors suitable for the present invention are disclosed, for example, in U.S. Patent No. 6,097,114 to Hazelton, U.S. Patent No. 6,114,781 to Hazelton *et al.*, and U.S. Patent No. 6,188,147 B1 to Hazelton *et al.*, the contents of which are hereby incorporated by reference in their entirety. A magnet array **304** is attached to a moving portion of a positioning stage **306**. Coils **308** of coil array **302** are attached to a fixed platen **310**. In this embodiment, magnet array **304** is sized such that four groups of coils **308** (16 coils) fit underneath magnet array **304**. Coils **308** can be switched electrically such that only the coils that are underneath magnet array **304** for producing force are energized. The other coils are switched off to minimize heating of the system. Magnet array **304** is configured to provide a magnetic flux field that interacts with coil array **302** to produce forces to move positioning stage **306** in three degrees of freedom (conventionally designated X, Y, θ_z) above coil array **302**. Although not shown in **Fig. 3**, air bearings and associated smooth, hard surfaces may be provided to facilitate movement of magnet array **304** with respect to coil array **302**.

As shown in the plan view of **Fig. 4**, in the preferred embodiment, magnet array **304** includes centrally-located, full-sized square magnets **312**, peripherally-located half magnets **314**, and quarter magnets **316** at the four corners. Half magnets **314** generate substantially one-half of the magnetic flux of full-sized magnets **312**, while quarter magnets **316** generate substantially one-quarter of said flux. The half magnets **314** and quarter magnets **316** provide efficient magnetic flux coupling with full-sized magnets **312**. Magnet array **304** is disposed about a center of gravity or origin **318**, and magnets **312, 314, 316**

form rows in the X direction and columns in the Y direction as defined by X and Y coordinate axes. Using these axes, the magnetic pitch of the array is defined as one-half the distance along a particular axis between centers of adjacent full-sized magnets **312**. Each full-sized magnet **312** has a length of about 1 pitch, p, and an area of about one pitch squared (p^2), as shown graphically.

Turning to **Fig. 5**, magnet array **304** is disposed above coils **308** which are arranged in the current embodiment in a 6×6 square array. Six coils are in each column $\mathbf{C_0}$, $\mathbf{C_1}$, $\mathbf{C_2}$, $\mathbf{C_3}$, $\mathbf{C_4}$, $\mathbf{C_5}$ and six coils are in each row $\mathbf{R_0}$, $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_3}$, $\mathbf{R_4}$, $\mathbf{R_5}$, thus forming an array of thirty-six coils **308**. As will be described shortly, the combination of magnet array **304** and an array of coils **308** permits planar motor control in 3 degrees of freedom - x- and y- translation and z- rotation. Each coil **308** has a length of about 3 pitch, 3p, and an area of about $9p^2$, as shown graphically. Persons of ordinary skill in the art will appreciate that the present invention may be readily adapted to control magnet arrays of different dimensions based on the teachings set forth herein. Preferably, a 5×5 or larger array of coils **308** is used, and the size of the coil array is selected in part based on the desired travel range for magnet array **304**. In other embodiments, the numbers of rows and columns in a magnet array may be substantially larger and/or the number of rows and the number of columns may be unequal.

Fig. 6 shows the magnet force constant, K_m, for magnet array **304** of planar motor **300**. In order to create X- and Y- translation forces, according to the Lorentz law, the two dimensional magnetic force constant, K_m, may be mathematically derived for a 2-dimensional planar motor. The moving magnet force constant coefficient curve is shown in **Fig. 6A**. As can be seen from **Fig. 6A**, the force constant magnitude has a trapezoid shape in both the x- and y-directions. The force constant coefficient curve may be used to derive equations for the x- and y- magnetic force constant. Referring to **Fig. 6A**, the moving magnet force constant amplitude, A, in x-movement with respect to portion A_1 (corresponding to Im x) is as follows:

$$A_{xx}(x_1,y_1) := \left| \begin{array}{l} a \leftarrow 1.0 \text{ if } 0 \le |x_1| < 4.5 \\ a \leftarrow -1\cdot\frac{1}{3}\cdot|x_1| + 2.5 \text{ if } 4.5 \le |x_1| < 7.5 \\ a \leftarrow 0 \text{ if } 7.5 \le |x_1| \end{array} \right. ; \quad (1)$$

$$A_{xy}(x_1,y_1) := \left| \begin{array}{l} a \leftarrow 1.0 \text{ if } 0 \le |y_1| < 4.5 \\ a \leftarrow -0.5\cdot|y_1| + 3.25 \text{ if } 4.5 \le |y_1| < 5.5 \\ a \leftarrow 0.5 \text{ if } 5.5 \le |y_1| < 6.5 \\ a \leftarrow -0.5\cdot|y_1| + 3.75 \text{ if } 6.5 \le |y_1| < 7.5 \\ a \leftarrow 0 \text{ if } 7.5 \le |y_1| \end{array} \right. ; \quad (2)$$

$$A_x(x_1,y_1) := A_{xx}(x_1,y_1)\cdot A_{xy}(x_1,y_1)\cdot k_x. \quad (3)$$

Further, with respect to portion A_2 the moving magnet force constant amplitude, A_x is as follows with respect to y-movement:

$$A_{yx}(x_1,y_1) := \left| \begin{array}{l} a \leftarrow -0.5\cdot|x_1| \text{ if } 0 \le |x_1| < 4.5 \\ a \leftarrow -0.5\cdot|x_1| + 3.25 \text{ if } 4.5 \le |x_1| < 5.5 \\ a \leftarrow 0.5 \text{ if } 5.5 \le |x_1| < 6.5 \\ a \leftarrow -0.5\cdot|x_1| + 3.75 \text{ if } 6.5 \le |x_1| < 7.5 \\ a \leftarrow 0 \text{ if } 7.5 \le |x_1| \end{array} \right. ; \quad (4)$$

$$A_{yy}(x_1,y_1) := \left| \begin{array}{l} a \leftarrow 1.0 \text{ if } 0 \le |y_1| < 4.5 \\ a \leftarrow -1\cdot\frac{1}{3}\cdot|y_1| + 2.5 \text{ if } 4.5 \le |y_1| < 7.5 \\ a \leftarrow 0 \text{ if } 7.5 \le |y_1| \end{array} \right. ; \quad (5)$$

$$A_y(x_1,y_1) := A_{yx}(x_1,y_1)\cdot A_{yy}(x_1,y_1)\cdot k_y. \quad (6)$$

Figs. 6B and **6C** show graphical representations of the Im x and Im y components, respectively, of the magnetic force constant, where coordinates (42, 42) are equivalent to position (0,0) at the intersection of the x- and y- axes in **Fig. 5**.

Referring again to **Fig. 5**, the magnet force constant for a given row of coils may be determined. For example, with the origin used for (x_1, y_1), the coils at positions $(R_2,$

$$k_{ma}(x_1,y_1) := \begin{bmatrix} A_x(-x_1-6,-y_1)\cdot P_1 & A_x(-x_1-3,-y_1)\cdot P_2 & A_x(-x_1-0,-y_1)\cdot P_3 \\ A_y(-x_1-6,-y_1)\cdot P_4 & A_x(-x_1-3,-y_1)\cdot P_5 & A_x(-x_1-0,-y_1)\cdot P_6 \\ 0 & 0 & 0 \end{bmatrix} \quad (7)$$

$C_0)$, (R_2, C_1), and (R_2, C_2) contribute the following to the magnetic force constant: where

$$P_1 = \sin\left(-x_1 \cdot \tfrac{\pi}{2} - 6 \cdot \tfrac{\pi}{2}\right) \cdot \cos\left(-y_1 \cdot \tfrac{\pi}{2}\right); \qquad P_2 = \sin\left(-x_1 \cdot \tfrac{\pi}{2} - 3 \cdot \tfrac{\pi}{2}\right) \cdot \cos\left(-y_1 \cdot \tfrac{\pi}{2}\right); \qquad (8)$$
$$P_3 = \sin\left(-x_1 \cdot \tfrac{\pi}{2} - 0 \cdot \tfrac{\pi}{2}\right) \cdot \cos\left(-y_1 \cdot \tfrac{\pi}{2}\right);$$

and

$$P_4 = \cos\left(-x_1 \cdot \tfrac{\pi}{2} - 6 \cdot \tfrac{\pi}{2}\right) \cdot \sin\left(-y_1 \cdot \tfrac{\pi}{2}\right); \qquad P_5 = \cos\left(-x_1 \cdot \tfrac{\pi}{2} - 3 \cdot \tfrac{\pi}{2}\right) \cdot \sin\left(-y_1 \cdot \tfrac{\pi}{2}\right); \qquad (9)$$
$$P_6 = \cos\left(-x_1 \cdot \tfrac{\pi}{2} - 0 \cdot \tfrac{\pi}{2}\right) \cdot \sin\left(-y_1 \cdot \tfrac{\pi}{2}\right).$$

Similarly, the coils at positions (R_2, C_3), (R_2, C_4), and (R_2, C_5) contribute the following to the magnetic force constant:

$$k_{mb}(x_1, y_1) := \begin{bmatrix} A_x(-x_1+3, y_1) \cdot P_7 & A_x(-x_1+6, y_1) \cdot P_8 & A_x(-x_1+9, y_1) \cdot P_9 \\ A_y(-x_1+3, y_1) \cdot P_{10} & A_x(-x_1+6, y_1) \cdot P_{11} & A_x(-x_1+9, y_1) \cdot P_{12} \\ 0 & 0 & 0 \end{bmatrix} \qquad (10)$$

where

$$P_7 = \sin\left(-x_1 \cdot \tfrac{\pi}{2} + 3 \cdot \tfrac{\pi}{2}\right) \cdot \cos\left(-y_1 \cdot \tfrac{\pi}{2}\right); \qquad P_8 = \sin\left(-x_1 \cdot \tfrac{\pi}{2} + 6 \cdot \tfrac{\pi}{2}\right) \cdot \cos\left(-y_1 \cdot \tfrac{\pi}{2}\right); \qquad (11)$$
$$P_9 = \sin\left(-x_1 \cdot \tfrac{\pi}{2} + 9 \cdot \tfrac{\pi}{2}\right) \cdot \cos\left(-y_1 \cdot \tfrac{\pi}{2}\right);$$

and

$$P_{10} = \cos\left(-x_1 \cdot \tfrac{\pi}{2} + 3 \cdot \tfrac{\pi}{2}\right) \cdot \sin\left(-y_1 \cdot \tfrac{\pi}{2}\right); \qquad P_{11} = \cos\left(-x_1 \cdot \tfrac{\pi}{2} + 6 \cdot \tfrac{\pi}{2}\right) \cdot \sin\left(-y_1 \cdot \tfrac{\pi}{2}\right); \qquad (12)$$
$$P_{12} = \cos\left(-x_1 \cdot \tfrac{\pi}{2} + 9 \cdot \tfrac{\pi}{2}\right) \cdot \sin\left(-y_1 \cdot \tfrac{\pi}{2}\right).$$

With reference to **Fig. 7**, row $\mathbf{R_2}$ of coils **308** is shown with magnets **312, 314** of magnet array **304** positioned thereabout. Magnets **312, 314** span a total distance $\mathbf{D_1}$ along the X-axis, which length is equal to the length spanned by four complete coils **308**. Thus, preferably, at least five coils **308** are provided in each row so that magnets **312, 314** may be translated with respect to coils **308**. In addition, in the preferred embodiment, distance $\mathbf{D_1}$ is about 430 mm. The array of magnets disposed along the X-axis includes five full-sized magnets **312** and two half magnets **314**, which is numerically equivalent to six full-sized magnets **312** each having an area of about one pitch squared (p^2). Also, extending between half magnets **314** along the X-axis, open square non-magnet portions **320** use the equivalent area of six full-sized magnets **312**, and so the magnet array uses the total equivalent area of twelve full-sized magnets **312**. The preferred embodiment has a pitch, therefore, of the ratio of $\mathbf{D_1}$ to 12, or 430/12 mm. Notably, in the embodiment of planar motor **304** discussed herein, magnets **312, 314** along the X-axis alternate in North (N) - South (S) polarity. Each change in unit pitch also is equal to a 90° phase difference as

encountered with sine or cosine functions; while magnet **312** at origin **318** is described as having an N-polarity and being at 0°, adjacent magnets with an S-polarity have a 180° phase difference.

The combination of row $\mathbf{R_2}$ of coils **308** and magnets **312, 314** of magnet array **304** produces a translational force along the X-axis. To create a four-phase linear motor, the magnet force constants, K_m, located above each coil **308** are determined. The force constant of magnet **312** located above coil **308** in column $\mathbf{C_2}$, which coincides with commutation origin **318**, is constructed as follows:

$$K_{x_{mag(0)}} = K_a \sin(x + 0) \qquad (13)$$

Thus, K_a is the peak-to-peak amplitude of the magnet force constant, K_m. Similarly, the force constants of magnets **312** located above coils **308** in columns $\mathbf{C_3}$, $\mathbf{C_2}$, respectively, are as follows:

$$K_{x_{mag(3)}} = K_a \sin\left(x + 3\tfrac{\pi}{2}\right) \qquad (14)$$

$$K_{x_{mag(-3)}} = K_a \sin\left(x - 3\tfrac{\pi}{2}\right) \qquad (15)$$

It should be noted that the factors of 3 in Eqs. 14 and 15 above are due to the offset of the respective coils a distance of 3 pitch from origin **318**. Finally, the force constants of magnets **314** located above coils **308** in columns $\mathbf{C_4}$, $\mathbf{C_0}$, respectively, are as follows:

$$K_{x_{mag(-6)}} = \tfrac{1}{2} K_a \sin\left(x - 6\tfrac{\pi}{2}\right); \qquad (16)$$
$$K_{x_{mag(6)}} = \tfrac{1}{2} K_a \sin\left(x + 6\tfrac{\pi}{2}\right). \qquad (17)$$

As indicated in Eqs. 16 and 17, the factors of 6 are due to the offset of the respective coils a distance of 6 pitch from origin **318**, while the factors of ½ account for the half-size of magnets **314**.

Next, to create a driving force in the X-direction and located at the center of each coil **308**, assuming the current in each coil **308** has the same phase as the respective magnet force constant, the following currents are required for coils **308** in columns $\mathbf{C_1}$, $\mathbf{C_2}$, $\mathbf{C_3}$, $\mathbf{C_4}$, $\mathbf{C_5}$:

$$I_{x(-6)} = I\sin\left(x - 6\tfrac{\pi}{2}\right); \tag{18}$$

$$I_{x(-3)} = I\sin\left(x - 3\tfrac{\pi}{2}\right); \tag{19}$$

$$I_{x(0)} = I\sin\left(x + 0\tfrac{\pi}{2}\right); \tag{20}$$

$$I_{x(3)} = I\sin\left(x + 3\tfrac{\pi}{2}\right); \tag{21}$$

$$I_{x(6)} = I\sin\left(x + 6\tfrac{\pi}{2}\right); \tag{22}$$

Thus, a total driving force, F, is the summation of the products of the individual driving forces and their respective force constants:

$$F = \tfrac{1}{2}I_{x(-6)}K_{x_{mag(-6)}} + I_{x(-3)}K_{x_{mag(-3)}} + I_{x(0)}K_{x_{mag(0)}} + I_{x(3)}K_{x_{mag(3)}} + \tfrac{1}{2}I_{x(6)}K_{x_{mag(6)}} \tag{23}$$

Equation 24 may be simplified with the following relations.

$$\tfrac{1}{2}I_{x(-6)}K_{x_{mag(-6)}} = \tfrac{1}{2}I_{x(6)}K_{x_{mag(6)}} = \tfrac{1}{2}IK_a\sin^2(x); \tag{24}$$

$$I_{x(-3)}K_{x_{mag(-3)}} = I_{x(3)}K_{x_{mag(3)}} = IK_a\cos^2(x); \tag{25}$$

$$I_{x(0)K_{x_{mag(0)}}} = IK_a\sin^2(x). \tag{26}$$

And upon simplification, the total force generated at row $\mathbf{R_2}$ becomes:

$$F = 2IK_a\left[\sin^2(x) + \cos^2(x)\right] = 2IK_a \tag{27}$$

Equation 27 may be further extended, so that the force generated at row $\mathbf{R_2}$ by coils **308** at locations (0,0), (3,0), (6,0), (-6,0), and (-3,0) is described as:

Row 2: (28)

$$\begin{aligned}F_x = {} & K_x \sin(x+0)\cos(y)\left[I_x \sin(x+0)\cos(y) + I_y \sin(y)\cos(x+0)\right] + \\ & K_x \sin(x+90)\cos(y)\left[I_x \sin(x+90)\cos(y) + I_y \sin(y)\cos(x+90)\right] + \\ & \tfrac{1}{2} K_x \sin(x+180)\cos(y)\left[I_x \sin(x+180)\cos(y) + I_y \sin(y)\cos(x+180)\right] + \\ & \tfrac{1}{2} K_x \sin(x+180)\cos(y)\left[I_x \sin(x+180)\cos(y) + I_y \sin(y)\cos(x+180)\right] + \\ & K_x \sin(x+270)\cos(y)\left[I_x \sin(x+270)\cos(y) + I_y \sin(y)\cos(x+270)\right] \\ = {} & 2I_x K_a \cos^2(y)\end{aligned}$$

As will be described shortly, if all coils 308 in rows $\mathbf{R_0}$, $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_3}$, $\mathbf{R_4}$, $\mathbf{R_5}$ are used to create a translational force in the X-direction, the equation for calculating the force simplifies to:

$$F_x = 4I_x K_a \qquad (29)$$

Similarly, the driving force in the Y-direction at column $\mathbf{C_2}$ created by coils **308** at locations (0,0), (0,3), (0,6), (0,-6), and (0,-3) is described as:

Column 2: (30)

$$\begin{aligned}F_y = {} & K_y \sin(y+0)\cos(x)\left[I_x \sin(x+0)\cos(y) + I_y \sin(y)\cos(x+0)\right] + \\ & K_y \sin(y+90)\cos(x)\left[I_x \sin(x+90)\cos(y) + I_y \sin(y+90)\cos(x)\right] + \\ & \tfrac{1}{2} K_y \sin(y+180)\cos(x)\left[I_x \sin(x+180)\cos(y) + I_y \sin(y+180)\cos(x)\right] + \\ & \tfrac{1}{2} K_y \sin(y+180)\cos(x)\left[I_x \sin(x+180)\cos(y) + I_y \sin(y+180)\cos(x)\right] + \\ & K_y \sin(y+270)\cos(x)\left[I_x \sin(x+270)\cos(y) + I_y \sin(y+270)\cos(x)\right] \\ = {} & 2I_y K_a \cos^2(x)\end{aligned}$$

Accounting for the force contributed by all of coils **308** in columns $\mathbf{C_0}$, $\mathbf{C_1}$, $\mathbf{C_2}$, $\mathbf{C_3}$, $\mathbf{C_4}$, $\mathbf{C_5}$, the total translational force in the Y-direction simplifies to:

$$F_y = 4I_y K_a \qquad (31)$$

It is desirable to provide torque or yaw control (θ_z) for the moving magnet planar motor so that control of a third degree of freedom complements the X- and Y-direction translational force control already discussed. In order to calculate torque, the distance from each of the coils to the center of gravity of the coil array must be known. To

this end, referring again to **Fig. 5**, it is noted that the distances between each of coils **308** are fixed. Thus, as shown in **Fig. 5**, the center points **CEN** of coils **308** in rows $\mathbf{R_0}$ and $\mathbf{R_4}$ are offset in the y-direction by distances $\mathbf{L_0}$, $\mathbf{L_4}$, respectively, from the x-axis that extends through origin **318**, the center points **CEN** of coils **308** in rows $\mathbf{R_1}$ **and** $\mathbf{R_3}$ are offset by distances $\mathbf{L_1}$, $\mathbf{L_3}$, respectively, and the center points **CEN** of coils **308** in row $\mathbf{R_2}$ are offset by a distance $\mathbf{L_2}$ from the X-axis, which is zero. Rows $\mathbf{R_0}$ and $\mathbf{R_4}$ each produce one-half of the force produced by each of rows $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_3}$, because of the difference in size of the magnets in the rows. At the position shown in **Fig. 5**, magnet array **304** is disposed only above rows $\mathbf{R_0}$, $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_3}$, $\mathbf{R_4}$, so that the total translation forces made by coils **308** in each of these rows is as follows:

$$F_{\text{row }0} = \frac{2I_uK_a\cos^2(y)}{2}; \qquad (32)$$

$$F_{\text{row }1} = 2I_uK_a\sin^2(y); \qquad (33)$$

$$F_{\text{row }2} = 2(I_u + I_l)K_a\cos^2(y); \qquad (34)$$

$$F_{\text{row }3} = 2I_lK_a\sin^2(y); \qquad (35)$$

$$F_{\text{row }4} = \frac{2I_lK_a\cos^2(y)}{2}. \qquad (36)$$

where "upper" rows $\mathbf{R_0}$, $\mathbf{R_1}$, $\mathbf{R_2}$ each have a current amplitude of I_u amps, and "lower" rows $\mathbf{R_2}$, $\mathbf{R_3}$, $\mathbf{R_4}$ each have a current amplitude of I_l amps.

The torque equation thus is derived as follows:

$$\begin{aligned} T_{\text{row}(y)} = {} & \tfrac{1}{2}L_0(2)I_uK_a\cos^2(y) + L_1(2)I_uK_a\sin^2(y) + L_2(2)(I_u + I_l)K_a\cos^2(y) \\ & - L_3(2)I_lK_a\sin^2(y) - \tfrac{1}{2}L_4(2)I_lK_a\cos^2(y) \end{aligned} \qquad (37)$$

The current used to generate the torque is defined such that I_u=-I_l, thus eliminating the third term of Eq. 37 which then further simplifies to the following:

$$\begin{aligned} T_{\text{row}(y)} = {} & \tfrac{1}{2}L_0(2)I_uK_a\cos^2(y) + L_1(2)I_uK_a\sin^2(y) \\ & - L_3(2)I_lK_a\sin^2(y) - \tfrac{1}{2}L_4(2)I_lK_a\cos^2(y) \\ = {} & (L_0 + L_4)I_uK_a\cos^2(y) + (L_1 + L_3)(2)I_uK_a\sin^2(y) \end{aligned} \qquad (38)$$

The offset distances $\mathbf{L_0}$, $\mathbf{L_1}$, $\mathbf{L_2}$, $\mathbf{L_3}$, $\mathbf{L_4}$ are fixed, and in the preferred embodiment, the value of $(\mathbf{L_0} + \mathbf{L_4})$ is fixed at 12 pitches while the value of $(\mathbf{L_1} + \mathbf{L_3})$ is fixed at 6 pitches. Equation 38 may be further simplified as:

$$T_{row(y)} = 12 I_u K_a\left[\sin^2(y) + \cos^2(y)\right] = 12 K_a I_{u(row)} \quad (39)$$

The θ_z torque thus may be created by a row of coils **308**. In addition, a column of coils **308** also may produce the θ_z torque, which is similarly determined to be as follows:

$$T_{column(x)} = 12 K_a I_{u(column)} \quad (40)$$

Moreover, both a row and column of coils **308** may be used to produce the θ_z torque with one-half the desired torque produced by each of the column and row.

In order to generate torque, the amplitude of the current supplied to a coil **308** is as follows:

$$I_x = \frac{F_x}{4K_a}; \quad (41)$$

$$I_y = \frac{F_y}{4K_a}. \quad (42)$$

The current for a row and column of coils is found to be as follows:

$$I_{u(row)} = \frac{T_{row(y)}}{12K_a}; \quad (43)$$

$$I_{u(column)} = \frac{T_{column(x)}}{12K_a}. \quad (44)$$

With the above equations, the amplitude of the coil current may be determined as a function of the desired translational force and torque.

Equations 32 to 44 can be applied with both the X- and Y-axial positions varying between about -0.5 pitch and about +0.5 pitch. This application constraint, however, places a significant restriction on the available planar motor moving area. To extend the area of movement, a switching function is used for coil row energization, as follows:

$$
I_{tzx}\left(x_1, y_1, T_{z_1}\right) := \left|
\begin{array}{ll}
I_{tzx_0} \leftarrow -\frac{T_{z_1}}{6 \cdot k_y \cdot 2} & \text{if } -1.5 \le y_1 \le 2.0 \\
I_{tzx_0} \leftarrow 0 & \text{otherwise} \\
I_{tzx_1} \leftarrow -\frac{T_{z_1}}{6 \cdot k_y \cdot 2} & \text{if } -1.5 \le y_1 \le 4.0 \\
I_{tzx_1} \leftarrow 0 & \text{otherwise} \\
I_{tzx_2} \leftarrow -\frac{T_{z_1}}{6 \cdot k_y \cdot 2} & \text{if } -1.5 \le y_1 \le 1.0 \\
I_{tzx_2} \leftarrow -\frac{T_{z_1}}{6 \cdot k_y \cdot 2} & \text{if } 1.0 \le y_1 \le 4.5 \\
I_{tzx_2} \leftarrow 0 & \text{otherwise} \\
I_{tzx_3} \leftarrow -\frac{T_{z_1}}{6 \cdot k_y \cdot 2} & \text{if } -1.5 \le y_1 \le 2.0 \\
I_{tzx_3} \leftarrow -\frac{T_{z_1}}{6 \cdot k_y \cdot 2} & \text{if } 4.0 \le y_1 \le 4.5 \\
I_{tzx_3} \leftarrow 0 & \text{otherwise} \\
I_{tzx_4} \leftarrow -\frac{T_{z_1}}{6 \cdot k_y \cdot 2} & \text{if } -1.0 \le y_1 \le 4.5 \\
I_{tzx_4} \leftarrow 0 & \text{otherwise} \\
I_{tzx_5} \leftarrow -\frac{T_{z_1}}{6 \cdot k_y \cdot 2} & \text{if } 1.0 \le y_1 \le 4.5 \\
I_{tzx_5} \leftarrow 0 & \text{otherwise} \\
\multicolumn{2}{c}{I_{tzx} \leftarrow \frac{I_{tzx}}{2}}
\end{array}
\right. \qquad (45)
$$

A switching function for coil column energization is as follows:

$$I_{tzy}\left(x_1, y_1, T_{z_1}\right) := \left| \begin{array}{ll} I_{tzy_0} \leftarrow -\frac{T_{z1}}{6 \cdot k_x \cdot 2} & \text{if } -1.5 \leq x_1 \leq 2.0 \\ I_{tzy_0} \leftarrow 0 & \text{otherwise} \\ I_{tzy_1} \leftarrow -\frac{T_{z1}}{6 \cdot k_x \cdot 2} & \text{if } -1.5 \leq x_1 \leq 4.0 \\ I_{tzy_1} \leftarrow 0 & \text{otherwise} \\ I_{tzy_2} \leftarrow -\frac{T_{z1}}{6 \cdot k_x \cdot 2} & \text{if } -1.5 \leq x_1 \leq 1.0 \\ I_{tzy_2} \leftarrow -\frac{T_{z1}}{6 \cdot k_x \cdot 2} & \text{if } 1.0 \leq x_1 \leq 4.5 \\ I_{tzy_2} \leftarrow 0 & \text{otherwise} \\ I_{tzy_3} \leftarrow -\frac{T_{z1}}{6 \cdot k_x \cdot 2} & \text{if } -1.5 \leq x_1 \leq 2.0 \\ I_{tzy_3} \leftarrow -\frac{T_{z1}}{6 \cdot k_x \cdot 2} & \text{if } 4.0 \leq x_1 \leq 4.5 \\ I_{tzy_3} \leftarrow 0 & \text{otherwise} \\ I_{tzy_4} \leftarrow -\frac{T_{z1}}{6 \cdot k_x \cdot 2} & \text{if } -1.0 \leq x_1 \leq 4.5 \\ I_{tzy_4} \leftarrow 0 & \text{otherwise} \\ I_{tzy_5} \leftarrow -\frac{T_{z1}}{6 \cdot k_x \cdot 2} & \text{if } 1.0 \leq x_1 \leq 4.5 \\ I_{tzy_5} \leftarrow 0 & \text{otherwise} \\ I_{tzy} \leftarrow \frac{I_{tzy}}{2} & \end{array} \right. \qquad (46)$$

For example, the switching function of Eq. 45 is applied as follows. To create desired torque over the entire planar motor moving area, a row $\mathbf{R_0}$ activation function is used. When magnet array **304** is located between -1.5 pitch and 2.0 pitch, row $\mathbf{R_0}$ torque control current is energized; otherwise, row $\mathbf{R_0}$ torque control current is turned off. Similarly, row $\mathbf{R_1}$ coils are energized when magnet array **304** is located between about -1.5 pitch to about 4.0 pitch; otherwise, row $\mathbf{R_1}$ coils are turned off. In the preferred embodiment, the switching function of Eq. 45 allows the desired torque to be generated with magnet array **304** at a wide range of locations.

The simultaneous generation of X- and Y- translational movement and θ_z rotational movement is governed by the following equations, in which the magnet force constant is multiplied by the sum of the commutation functions for translational force and torque, for each row of coils **308**:

For row 2: (47)

$$F_x = K_x \sin(x+0)\cos(y)\begin{bmatrix}(I_x + I_{t(r2)})\sin(x+0)\cos(y) + \\ (I_{y(c2)} + I_{t(c2)})\sin(y)\cos(x)\end{bmatrix} +$$

$$K_x \sin(x+90)\cos(y)\begin{bmatrix}(I_x + I_{t(r2)})\sin(x+90)\cos(y) + \\ (I_{y(c1)} + I_{t(c1)})\sin(y)\cos(x+90)\end{bmatrix} +$$

$$\tfrac{1}{2}K_x \sin(x+180)\cos(y)\begin{bmatrix}(I_x + I_{t(r2)})\sin(x+180)\cos(y) + \\ (I_{y(c0)} + I_{t(c0)})\sin(y)\cos(x+180)\end{bmatrix} +$$

$$\tfrac{1}{2}K_x \sin(x+0)\cos(y)\begin{bmatrix}(I_x + I_{t(r2)})\sin(x+0)\cos(y) + \\ (I_{y(c4)} + I_{t(c4)})\sin(y)\cos(x)\end{bmatrix} +$$

$$K_x \sin(x+270)\cos(y)\begin{bmatrix}(I_x + I_{t(r2)})\sin(x+270)\cos(y) + \\ (I_{y(c3)} + I_{t(c3)})\sin(y)\cos(x+270)\end{bmatrix}$$

$$= 2(I_x + I_{t(r2)})K_a \cos^2(y)$$

$$= 2I_x K_a \cos^2(y) + 2I_{t(r2)} K_a \cos^2(y)$$

For row 1: (48)

$$F_x = K_x \sin(x+0)\cos(y+90)\begin{bmatrix}(I_x + I_{t(r1)})\sin(x+0)\cos(y+90) + \\ (I_{y(c2)} + I_{t(c2)})\sin(y+90)\cos(x)\end{bmatrix} +$$

$$K_x \sin(x+90)\cos(y+90)\begin{bmatrix}(I_x + I_{t(r1)})\sin(x+90)\cos(y+90) + \\ (I_{y(c1)} + I_{t(c1)})\sin(y+90)\cos(x+90)\end{bmatrix} +$$

$$\tfrac{1}{2}K_x \sin(x+180)\cos(y+90)\begin{bmatrix}(I_x + I_{t(r1)})\sin(x+180)\cos(y+90) + \\ (I_{y(c0)} + I_{t(c0)})\sin(y+90)\cos(x+180)\end{bmatrix} +$$

$$\tfrac{1}{2}K_x \sin(x+180)\cos(y+90)\begin{bmatrix}(I_x + I_{t(r1)})\sin(x+180)\cos(y+90) + \\ (I_{y(c4)} + I_{t(c4)})\sin(y+90)\cos(x+180)\end{bmatrix} +$$

$$K_x \sin(x+270)\cos(y+90)\begin{bmatrix}(I_x + I_{t(r1)})\sin(x+270)\cos(y+90) + \\ (I_{y(c3)} + I_{t(c3)})\sin(y+90)\cos(x+270)\end{bmatrix}$$

$$= 2I_x K_a \sin^2(y) + 2I_{t(r1)} K_a \sin^2(y)$$

For row 0: (49)

$$F_x = \tfrac{1}{2}K_x \sin(x+0)\cos(y+180)\begin{bmatrix}\left(I_x + I_{t(r0)}\right)\sin(x+0)\cos(y+180)+ \\ \left(I_{y(c2)} + I_{t(c2)}\right)\sin(y+180)\cos(x)\end{bmatrix}+$$

$$\tfrac{1}{2}K_x \sin(x+90)\cos(y+180)\begin{bmatrix}\left(I_x + I_{t(r0)}\right)\sin(x+90)\cos(y+180)+ \\ \left(I_{y(c1)} + I_{t(c1)}\right)\sin(y+180)\cos(x+90)\end{bmatrix}+$$

$$\tfrac{1}{4}K_x \sin(x+180)\cos(y+180)\begin{bmatrix}\left(I_x + I_{t(r0)}\right)\sin(x+180)\cos(y+180)+ \\ \left(I_{y(c0)} + I_{t(c0)}\right)\sin(y+180)\cos(x+180)\end{bmatrix}+$$

$$\tfrac{1}{4}K_x \sin(x+180)\cos(y+180)\begin{bmatrix}\left(I_x + I_{t(r0)}\right)\sin(x+180)\cos(y+180)+ \\ \left(I_{y(c4)} + I_{t(c4)}\right)\sin(y+180)\cos(x+180)\end{bmatrix}+$$

$$\tfrac{1}{2}K_x \sin(x+270)\cos(y+180)\begin{bmatrix}\left(I_x + I_{t(r0)}\right)\sin(x+270)\cos(y+180)+ \\ \left(I_{y(c3)} + I_{t(c3)}\right)\sin(y+180)\cos(x+270)\end{bmatrix}$$

$$= 1I_x K_a \cos^2(y) + 1I_{t(r0)} K_a \cos^2(y)$$

For row 3: (50)

$$F_x = K_x \sin(x+0)\cos(y+90)\begin{bmatrix}\left(I_x + I_{t(r3)}\right)\sin(x+0)\cos(y+90)+ \\ \left(I_{y(c2)} + I_{t(c2)}\right)\sin(y+90)\cos(x)\end{bmatrix}+$$

$$K_x \sin(x+90)\cos(y+90)\begin{bmatrix}\left(I_x + I_{t(r3)}\right)\sin(x+90)\cos(y+90)+ \\ \left(I_{y(c1)} + I_{t(c1)}\right)\sin(y+90)\cos(x+90)\end{bmatrix}+$$

$$\tfrac{1}{2}K_x \sin(x+180)\cos(y+90)\begin{bmatrix}\left(I_x + I_{t(r3)}\right)\sin(x+180)\cos(y+90)+ \\ \left(I_{y(c0)} + I_{t(c0)}\right)\sin(y+90)\cos(x+180)\end{bmatrix}+$$

$$\tfrac{1}{2}K_x \sin(x+180)\cos(y+90)\begin{bmatrix}\left(I_x + I_{t(r3)}\right)\sin(x+180)\cos(y+90)+ \\ \left(I_{y(c4)} + I_{t(c4)}\right)\sin(y+90)\cos(x+180)\end{bmatrix}+$$

$$K_x \sin(x+270)\cos(y+90)\begin{bmatrix}\left(I_x + I_{t(r3)}\right)\sin(x+270)\cos(y+90)+ \\ \left(I_{y(c3)} + I_{t(c3)}\right)\sin(y+90)\cos(x+270)\end{bmatrix}$$

$$= 2I_x K_a \sin^2(y) + 2I_{t(r3)} K_a \sin^2(y)$$

For row 4: (51)

$$F_x = \tfrac{1}{2}K_x \sin(x+0)\cos(y+180)\begin{bmatrix}(I_x + I_{t(r4)})\sin(x+0)\cos(y+180)+\\(I_{y(c2)} + I_{t(c2)})\sin(y+180)\cos(x)\end{bmatrix}+$$

$$\tfrac{1}{2}K_x \sin(x+90)\cos(y+180)\begin{bmatrix}(I_x + I_{t(r4)})\sin(x+90)\cos(y+180)+\\(I_{y(c1)} + I_{t(c1)})\sin(y+180)\cos(x+90)\end{bmatrix}+$$

$$\tfrac{1}{4}K_x \sin(x+180)\cos(y+180)\begin{bmatrix}(I_x + I_{t(r4)})\sin(x+180)\cos(y+180)+\\(I_{y(c0)} + I_{t(c0)})\sin(y+180)\cos(x+180)\end{bmatrix}+$$

$$\tfrac{1}{4}K_x \sin(x+180)\cos(y+180)\begin{bmatrix}(I_x + I_{t(r4)})\sin(x+180)\cos(y+180)+\\(I_{y(c4)} + I_{t(c4)})\sin(y+180)\cos(x+180)\end{bmatrix}+$$

$$\tfrac{1}{2}K_x \sin(x+270)\cos(y+180)\begin{bmatrix}(I_x + I_{t(r4)})\sin(x+270)\cos(y+180)+\\(I_{y(c3)} + I_{t(c3)})\sin(y+180)\cos(x+270)\end{bmatrix}$$

$$= 1I_xK_a\cos^2(y) + 1I_{t(r4)}K_a\cos^2(y)$$

The total translational force in the X- direction is then determined by summing the contributions from each row of coils **308**:

$$\begin{aligned}F_{x(total)} &= F_{x(r0)} + F_{x(r1)} + F_{x(r2)} + F_{x(r3)} + F_{x(r4)} \\ &= 4I_xK_a\left[\sin^2(y) + \cos^2(y)\right] \\ &= 4K_aI_x\end{aligned} \quad (52)$$

Control of the θ_z rotational movement is accomplished by selecting the current I_x in Eqs. 47 to 51. A similar approach is used to Y- direction translational control. Control of the rotational force is accomplished by selecting the current $I_{t(r)}$ in Eqs. 47 to 51. Torque control currents are determined as follows, with magnet array **304** located as shown in **Fig. 5**:

$$I_{t_{r0}}, I_{t_{r1}} = \frac{Torque_x}{12K_a}; \tag{53}$$

$$I_{t_{r2}} = \frac{Torque_x}{12K_a} - \frac{Torque_x}{12K_a} = 0; \tag{54}$$

$$I_{t_{r3}}, I_{t_{r4}} = -\frac{Torque_x}{12K_a}; \tag{55}$$

$$\begin{aligned} T_{x_{total}} &= 6I_{t_{r1}}K_a \sin^2(y) + 6I_{t_{r0}}K_a \sin^2(y) + 6I_{t_{r4}}K_a \cos^2(y) + \\ &\quad 6I_{t_{r3}}K_a \cos^2(y) \\ &= 12I_{t_r}K_a\left[\sin^2(y) + \cos^2(y)\right] \\ &= 12K_a I_{t_r} \end{aligned} \tag{56}$$

$$I_{t_r} = \frac{Torque_x}{12K_a}$$

Turning now to the treatment of undesirable cross coupling between translational forces and θ_z rotational movement, it should first be noted that the symmetrical alignment of magnet array **304** with respect to coils **308**, as shown in **Fig. 5**, permits translation in the X- direction without undesired torque. However, if the position of magnet array **304** with respect to coils **308** is changed, for example, to that shown in **Fig. 8**, driving translational forces are no longer symmetrically generated and torque compensation is desired. Such compensation may be achieved with the following method: (1) applying an X- direction translational force to magnet array **304** and measuring the undesired torque; (2) normalizing the measured undesirable torque to create a predictor or model of the behavior with the undesired torque output preferably determined as a function of movement or offset of magnet array **304** in the Y- direction, measured in pitch; (3) substantially canceling the undesired torque using the behavior model and the torque control of Eqs. 52 to 56.

An exemplar model of undesirable torque behavior is shown in **Fig. 9**, with undesired torque (measured in units of Newton-meters) graphed as a function of displacement (measured in units of pitch). For example, movement of +1 pitch results in undesired torque of about 50 N-pitch.

Further, an exemplar model of undesired torque compensation for F_x is shown in **Fig. 9A** and a compensation model for F_y is shown in **Fig. 9B**.

Referring to **Figs. 10** and **11**, torque and translation force outputs are shown in response to translation force compensation of 100 N-pitch and 100 N, respectively, as magnet array **304** moves from y = -1.5 pitch to y = 4.5 pitch. Coupling between

translational force control and θ_z rotational movement control is shown to be substantially without coupling, with X- translation and θ_z rotation being independent.

Fig. 12 is a block diagram of a position control system **350** using an exemplary array of thirty-six coils **308** according to the present invention. Blocks $\mathbf{B_1}$ and $\mathbf{B_2}$, for example, represent the undesired torque compensation maps shown graphically in **Figs. 9A** and **9B**. The switch function of block $\mathbf{B_3}$ may be the switch function of Equations 44 and 45 as described above. The commutation block, $\mathbf{B_4}$, may be governed by Equations 47 to 51, particularly the portion in square brackets. The thirty-six coil current output of amplifier block **352** is supplied to a position loop control at block $\mathbf{B_5}$, at which time the force constant is multiplied by the above-mentioned bracketed commutation current in Equations 47 to 51. A total of twenty-five portions in square brackets are found in these equations, instead of 36, because the coil current is zero to position (R_5, C_5). Outputs x and y are measured in pitch, while output θ is measured in radians. Element 354 represents the amplitude of the control current for rows R_0 to R_5, while element 356 represents the amplitude of the control current for columns C_0 to C_5.

Fig. 13 is an elevational view, partially in section, showing a microlithographic apparatus **400** incorporating a planar motor-driven positioning stage **402** in accordance with the present invention. Microlithographic apparatus **400**, such as described in U.S. Pat. No. 5,528,118 to Lee, includes an upper optical system **404** and a lower wafer support and positioning system **406**. Optical system **404** includes an illuminator **408** containing a lamp **LMP**, such as a mercury vapor lamp, and an ellipsoidal mirror **EM** surrounding lamp **LMP**. Illuminator **408** also comprises an optical integrator, such as a fly's eye lens **FEL**, producing secondary light source images, and a condenser lens **CL** for illuminating a reticle (mask) **R** with uniform light flux. A mask holder **RST** holding mask or reticle **R** is mounted above a lens barrel **PL** of a projection optical system. A lens barrel **PL** is fixed on a part of a column assembly **410** which is supported on a plurality of rigid arms **412**, each mounted on the top portion of an isolation pad or block system **414**. Microlithographic apparatus **400** exposes a pattern of the reticle **R** onto a wafer **W**, while mask holder **RST** and positioning stage **402** are moving synchronously relative to illuminator **408**.

Inertial or seismic blocks **416** are located on the system, *e.g.* mounted on arms **412**. Blocks **416** can take the form of a cast box which can be filled with sand at the operation site to reduce the shipping weight of apparatus **400**. An object or positioning stage base **418** is supported from arms **412** by depending blocks **416** and depending bars **420** and horizontal bars **422**. Positioning stage **402** carrying wafer **W** is supported in a

movable fashion by positioning stage base **418**. A reaction frame **424** carries a magnet array (not shown) and drives positioning stage **402** in cooperation with a moving coil array (not shown). Reaction frame **424** is isolated from positioning stage base **418** in terms of vibration relative to a foundation **426**, when a force is generated as positioning stage **402** is driven. Positioning stage **402** and/or mask holder **RST** can be driven by a planar motor such as planar motor **300** described above.

There are a number of different types of photolithographic devices. For example, exposure apparatus **400** can be used as a scanning type photolithography system which exposes the pattern from reticle **R** onto wafer **W** with reticle **R** and wafer **W** moving synchronously. In a scanning type lithographic device, reticle **R** is moved perpendicular to an optical axis of lens assembly **404** by reticle stage **RST** and wafer **W** is moved perpendicular to an optical axis of lens assembly **404** by wafer stage **402**. Scanning of reticle **R** and wafer **W** occurs while reticle **R** and wafer **W** are moving synchronously.

Alternately, exposure apparatus **400** can be a step-and-repeat type photolithography system that exposes reticle **R** while reticle **R** and wafer **W** are stationary. In the step and repeat process, wafer **W** is in a constant position relative to reticle **R** and lens assembly **404** during the exposure of an individual field. Subsequently, between consecutive exposure steps, wafer **W** is consecutively moved by wafer stage **402** perpendicular to the optical axis of lens assembly **404** so that the next field of semiconductor wafer **W** is brought into position relative to lens assembly **404** and reticle **R** for exposure. Following this process, the images on reticle **R** are sequentially exposed onto the fields of wafer **W** so that the next field of semiconductor wafer **W** is brought into position relative to lens assembly **404** and reticle **R**.

However, the use of exposure apparatus **400** provided herein is not limited to a photolithography system for semiconductor manufacturing. Exposure apparatus **400**, for example, can be used as an LCD photolithography system that exposes a liquid crystal display device pattern onto a rectangular glass plate or a photolithography system for manufacturing a thin film magnetic head. Further, the present invention can also be applied to a proximity photolithography system that exposes a mask pattern by closely locating a mask and a substrate without the use of a lens assembly. Additionally, the present invention provided herein can be used in other devices, including other semiconductor processing equipment, machine tools, metal cutting machines, and inspection machines.

The illumination source **408** can be g-line (436 nm), i-line (365 nm), KrF excimer laser (248 nm), ArF excimer laser (193 nm) and F_2 laser (157 nm). Alternatively, illumination source **408** can also use charged particle beams such as x-ray and electron

beams. For instance, in the case where an electron beam is used, thermionic emission type lanthanum hexaboride (LaB_6) or tantalum (Ta) can be used as an electron gun. Furthermore, in the case where an electron beam is used, the structure could be such that either a mask is used or a pattern can be directly formed on a substrate without the use of a mask.

With respect to lens assembly **404**, when far ultra-violet rays such as the excimer laser are used, glass materials such as quartz and fluorite that transmit far ultra-violet rays are preferably used. When the F_2 type laser or x-ray is used, lens assembly **404** should preferably be either catadioptric or refractive (a reticle should also preferably be a reflective type), and when an electron beam is used, electron optics should preferably comprise electron lenses and deflectors. The optical path for the electron beams should be in a vacuum.

Also, with an exposure device that employs vacuum ultra-violet radiation (VUV of wavelength 200 nm or lower, use of the catadioptric type optical system can be considered. Examples of the catadioptric type of optical system include the disclosure Japan Patent Application Disclosure No. 8-171054 published in the Official Gazette for Laid-Open Patent Applications and its counterpart U.S. Patent No. 5,668,672, as well as Japan Patent Application Disclosure No. 10-20195 and its counterpart U.S. Patent No. 5,835,275. In these cases, the reflecting optical device can be a catadioptric optical system incorporating a beam splitter and concave mirror. Japan Patent Application Disclosure No. 8-334695 published in the Official Gazette for Laid-Open Patent Applications and its counterpart U.S. Patent No. 5,689,377 as well as Japan Patent Application Disclosure No. 10-3039 and its counterpart European Patent Application EP 0816892 A2 also use a reflecting-refracting type of optical system incorporating a concave mirror, etc., but without a beam splitter, and can also be employed with this invention. The disclosures in the above-mentioned U.S. patents, European patent application, as well as the Japan patent applications published in the Official Gazette for Laid-Open Patent Applications are incorporated herein by reference.

Further, in photolithography systems, when linear motors (see U.S. Patent Nos. 5,623,853 or 5,528,118) are used in a wafer stage or a reticle stage, the linear motors can be either an air levitation type employing air bearings or a magnetic levitation type using Lorentz force or reactance force. Additionally, the stage could move along a guide, or it could be a guideless type stage which uses no guide. The disclosures in U.S. Patent Nos. 5,623,853 and 5,528,118 are incorporated herein by reference.

Alternatively, one of the stages could be driven by a planar motor, which drives the stage by electromagnetic force generated by a magnet unit having two-dimensionally arranged magnets and an armature coil unit having two-dimensionally arranged coils in facing positions. With this type of driving system, either one of the magnet unit or the armature coil unit is connected to the stage and the other unit is mounted on the moving plane side of the stage.

Movement of the stages as described above generates reaction forces which can affect performance of the photolithography system. Reaction forces generated by the wafer (substrate) stage motion can be mechanically released to the floor (ground) by use of a frame member as described in U.S. Patent No. 5,528,118 and published Japanese Patent Application Disclosure No. 8-166475. Additionally, reaction forces generated by the reticle (mask) stage motion can be mechanically released to the floor (ground) by use of a frame member as described in U.S. Patent No. 5,874,820 and published Japanese Patent Application Disclosure No. 8-330224. The disclosures in U.S. Patent Nos. 5,528,118 and 5,874,820 and Japanese Patent Application Disclosure No. 8-330224 are incorporated herein by reference.

As described above, a photolithography system according to the above-described embodiments can be built by assembling various subsystems, including each element listed in the appended claims, in such a manner that prescribed mechanical accuracy, electrical accuracy and optical accuracy are maintained. In order to maintain the various accuracies, prior to and following assembly, every optical system is adjusted to achieve its optical accuracy. Similarly, every mechanical system and every electrical system are adjusted to achieve their respective mechanical and electrical accuracies. The process of assembling each subsystem into a photolithography system includes mechanical interfaces, electrical circuit wiring connections and air pressure plumbing connections between each subsystem. Needless to say, there is also a process where each subsystem is assembled prior to assembling a photolithography system from the various subsystems. Once a photolithography system is assembled using the various subsystems, total adjustment is performed to make sure that every accuracy is maintained in the complete photolithography system. Additionally, it is desirable to manufacture an exposure system in a clean room where the temperature and humidity are controlled.

Further, semiconductor devices can be fabricated using the above-described systems, by the process shown generally in **Fig. 14**. In step **501** the device's function and performance characteristics are designed. Next, in step **502**, a mask (reticle) having a pattern is designed according to the previous designing step, and in a parallel step **503**, a

wafer is made from a silicon material. The mask pattern designed in step **502** is exposed onto the wafer from step **503** in step **504** by a photolithography system described hereinabove consistent with the principles of the present invention. In step **505** the semiconductor device is assembled (including the dicing process, bonding process and packaging process), and then finally the device is inspected in step **506**.

Fig. 15 illustrates a detailed flowchart example of the above-mentioned step **504** in the case of fabricating semiconductor devices. In step **511** (oxidation step), the wafer surface is oxidized. In step **512** (CVD step), an insulation film is formed on the wafer surface. In step **513** (electrode formation step), electrodes are formed on the wafer by vapor deposition. In step **514** (ion implantation step), ions are implanted in the wafer. The above-mentioned steps **511 -514** form the preprocessing steps for wafers during wafer processing, and selection is made at each step according to processing requirements.

At each stage of wafer processing, when the above-mentioned preprocessing steps have been completed, the following post-processing steps are implemented. During post-processing, initially, in step **515** (photoresist formation step), photoresist is applied to a wafer. Next, in step **516** (exposure step), the above-mentioned exposure device is used to transfer the circuit pattern of a mask (reticle) to a wafer. Then, in step **517** (developing step), the exposed wafer is developed, and in step **518** (etching step), parts other than residual photoresist (exposed material surface) are removed by etching. In step **519** (photoresist removal step), unnecessary photoresist remaining after etching is removed.

Multiple circuit patterns are formed by repetition of these preprocessing and post-processing steps.

It will be apparent to those skilled In the art that various modifications and variations can be made in the methods described, in the stage device, the control system, the material chosen for the present invention, and in construction of the photolithography systems as well as other aspects of the invention without departing from the scope or spirit of the invention.

While various descriptions of the present invention are described above, it should be understood that the various features can be used singly or in any combination thereof. Therefore, this invention is not to be limited to only the specifically preferred embodiments depicted herein.

Further, it should be understood that variations and modifications within the spirit and scope of the invention may occur to those skilled in the art to which the invention pertains. For example, magnet arrays and coil arrays having a different number of magnets and/or coils, respectively, from those discussed in detail herein may be used in accordance

with the principles of the present invention. Accordingly, all expedient modifications readily attainable by one versed in the art from the disclosure set forth herein that are within the scope and spirit of the present invention are to be included as further embodiments of the present invention. The scope of the present invention is accordingly defined as set forth in the appended claims.